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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**LOGISTICALLY-CONSTRAINED ASSET SCHEDULING
IN MARITIME SECURITY OPERATIONS**

by

Doyne Damian Clem

September 2008

Thesis Advisor:
Second Reader:

Johannes O. Royset
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**LOGISTICALLY-CONSTRAINED ASSET SCHEDULING IN MARITIME
SECURITY OPERATIONS**

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

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ABSTRACT

Operational commanders and planners are challenged with maintaining fleet presence in many environments with limited resources. To add to this challenge, there are further constraints placed upon assets allocated to a given operational commander such as replenishments at sea, multinational exercises, diplomatic port visits, and predetermined in-chop and out-chop dates. In the case of the Combined Maritime Force (CMF), which operates in the FIFTH FLEET Area of Responsibility, these constraints are further magnified by the fact that ships under his or her operational command are from as many as ten different coalition nations at any given time. Furthermore, command of the CMF rotates between these coalition nations, increasing the propensity for inconsistent and sub-optimal resource allocation. This thesis develops a scheduling tool, Coalition Resource Allocation for Maritime Security (C-RAMS) that is capable of quickly producing a schedule that optimizes a given measure of effectiveness for assets assigned to the CMF. This C-RAMS tool accounts for logistics requirements and allows a commander to set priorities within various sub-regions, types of assets, and specific time periods. We illustrate how C-RAMS provides such an optimal schedule and also provides insights into interactions between different priorities and ship types, including those which may be interpolated for future force configurations, through the use of Visual Basic with an Excel 2003 user interface.

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EXECUTIVE SUMMARY

Commanders must plan the locations and activities of several ships at a time to maintain presence, accomplish specific missions, and maintain fleet readiness. In the current environment of decreasing asset availability and increasing reliance on multinational operations, these demands are made even more difficult by the need for greater coordination and more efficient allocation of resources. This is certainly important in the FIFTH FLEET Area of Responsibility, where the Combined Maritime Force (CMF) is responsible for an area in excess of 2.5 million square miles. Assigned to the CMF are anywhere from eight to twelve vessels typically belonging to the United States, the United Kingdom, France, Italy, Pakistan, Australia, The Netherlands, and Bahrain, with command being rotated every three months within this pool of nations.

Although there are many complex decisions requiring the consideration of multiple factors in scheduling the assets of the CMF, there exists no uniform approach to planning as command is passed from one country to the next. Without such uniformity, the opportunity for less than desirable scheduling and underutilization of resources is significant.

This study develops the Coalition Resource Allocation for Maritime Security (C-RAMS) decision support tool for the scheduling of maritime assets, which is flexible enough to account for a wide range of daily scheduling constraints and mission priorities as set by a given commander. Furthermore, the output of the resulting scheduling tool provides useful information in the near term while also creating a baseline of study for future operations with the employment of augmenting technologies such as maritime Unmanned Aerial Vehicles. To maximize system compatibility, C-RAMS is written in Visual Basic with an Excel user interface.

In this study, we use a network model overlaid on a map of the FIFTH FLEET AOR, where each sea zone is a node in which a ship can produce a reward for its presence. In this geographic network, transit zones between sea zones are vertices that do not incur a reward, but may be scheduled to permit movement between sea zones to

increase a ship's reward or to move toward a future obligation such as a port visit or a replenishment-at-sea (RAS). We consider four sea zones representing the Red Sea, the Arabian Sea, the Western Indian Ocean, and the Arabian Gulf, respectively. Also represented in this geographic network are nodes adjacent to the four sea zones which account for pre-scheduled port visits, RASs, in-chopping into, and out-chopping from the control of the CMF Commander. This is then used to plan for 5 to 30 days at a time, using a network representation of possible ship positions and states.

With the geographic network and the first day's configuration of ship locations, we build a time-expanded configuration network. A column of configuration nodes is created in each following day based solely upon configurations which contain only ship positions and activities that are geographically adjacent (and therefore feasibly reachable) in one time step for each ship. Each resulting state is then added to a state vector which consists of each possible configuration for the given time step. Arcs represent feasible transitions between state vectors in successive days. This time-expanded configuration network is then implicitly built and solved utilizing a deterministic dynamic program to find a longest (i.e. maximum reward) path.

The decision support tool can be shared by US and coalition naval personnel for the scheduling of MSO ships in the FIFTH FLEET AOR. The Coalition Resource Allocation for Maritime Security decision support tool incorporates a given set of pre-existing mission commitments as parameters and provides an optimum employment strategy based on commander's intent and priorities. The output is a schedule that is feasible, and compatible with existing reporting requirements.

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I. INTRODUCTION

A. BACKGROUND

This study seeks to develop a decision support tool for the scheduling of maritime assets, particularly in the FIFTH FLEET Area of Responsibility, which is flexible enough to account for a wide range of scheduling constraints and varying degrees of priorities as set by a given commander. Furthermore, the output of the resulting scheduling tool may provide useful information in the near term while also creating a baseline of study for future operations with the employment of augmenting technologies such as maritime Unmanned Aerial Vehicles (UAVs). Finally, such a tool should be compatible with existing computer operating systems and software used by all interested nations.

1. Maritime Security Operations

In recent years, the United States Navy has dramatically increased the number of Maritime Security Operations (MSO) it performs in support of the Global War on Terror (GWOT) and various international agreements. The vast majority of these missions occur in the FIFTH FLEET Area of Responsibility (AOR) in conjunction with coalition forces under the auspices of the Combined Maritime Force (CMF). The CMF is comprised of Combined Task Forces (CTFs) 150, 152, and 158, each with a specific sub-AOR, and its own set of specific missions, geography, and challenges.

The scope of the challenges facing the CMF cannot be fully appreciated without first understanding the purpose of MSO. The official missions, as published by Commander, Combined Maritime Forces (CUSNC, 2008), are as follows:

Coalition and U.S. forces conduct MSO to help set the conditions for security and stability in the maritime environment, as well as complement the counter-terrorism and security efforts of regional nations.

MSO seek to disrupt violent extremists' use of the maritime environment as a venue for attack or to transport personnel, weapons or other material.

Coalition maritime forces conduct MSO in international waters in the Arabian Gulf, Arabian Sea, Gulf of Oman, Gulf of Aden, Indian Ocean and Red Sea.

MSO includes a full range of activities from assisting mariners in distress to Visit, Board, Search and Seizure operations to engaging regional and coalition navies.

More specifically, CTFs 150 and 152 share a common mission statement which encapsulates the broader vision of the CMF Commander: “To help set the conditions for security and stability in the maritime environment as well as complement the counter-terrorism and security efforts of regional nations. These operations deny international terrorists use of the maritime environment as a venue for attack or to transport personnel, weapons or other material” (CUSNC, 2008). The difference between these two CTFs being that 150 must cover the expanse of the Gulf of Aden, Gulf of Oman, the Arabian Sea, Red Sea and the Northwestern Indian Ocean, whereas CTF 152 is responsible for the South and Central Arabian Gulf. The Northern Arabian Gulf AOR belongs to CTF 158, which in addition to the common MSO mission is responsible for, “maintaining security in and around both the Al Basrah and Khawr Al Amaya Oil Terminals (ABOT and KAAOT, respectively), in support of U.N. Security Council Resolution 1723. This resolution charges the multinational force with the responsibility and authority to maintain security and stability in the Iraqi territorial waters and also supports the Iraqi government’s request for security support” (CUSNC, 2008).



Figure 1. FIFTH FLEET AOR.

The total AOR for the CMF is in excess of 2.5 million square miles and borders 21 countries spanning two continents and countless cultures. Assigned to the CMF are anywhere from eight to twelve vessels typically belonging to the United States, the United Kingdom, France, Italy, Pakistan, Australia, The Netherlands, and Bahrain. Ranging in size and capability, most assets assigned to one of the MSO CTFs are capable of employing helicopters and at least two boarding teams. Currently the largest platform to be assigned to MSO is a 390-man Ticonderoga-class cruiser (CG) of the U.S. Navy. When fully equipped, it carries two Light Airborne Multi Purpose System (LAMPS) SH-60B Helicopters, two small boats, 25mm machine gun, and various other crew-served

weapons. Conversely, the smallest platform typically assigned is the U.S. Coast Guard's 110-foot Cutter (USCGC). Also sporting a 25mm machine gun, the cutters carry two 50-caliber machine guns, miscellaneous small arms and a crew of 16.



Figure 2. USS CHANCELLORSVILLE (CG 62).



Figure 3. USCGC MUSTANG.

All coalition warships, regardless of nationality, appear on the spectrum of capabilities and armament between these two examples.

Given the vast area of the waters of the FIFTH FLEET AOR, the relatively small number of ships assigned to the CMF, and the multiple taskings of each of those ships, a

tool for optimally scheduling these assets would aid the CMF Commander in planning. Ideally, the CMF Commander would be able to assign priorities to specific areas and missions on a given time horizon—notionally two weeks—based on intelligence, seasonal traffic patterns, historical successes and failures, and task saturation. Given this data and asset availability, a desirable schedule is one that optimizes asset allocation to missions over the given time horizon. Once an optimal schedule is attained, the resulting data serves as a baseline for measuring the efficacy of the given assets upon which we perform a cost-benefit analysis of the employment of maritime Unmanned Aerial Vehicles (UAVs). Such analyses can assist in the decision of which and how many UAVs to procure and deploy with U.S. maritime assets.

2. UAV Employment

Not yet a mainstay in MSO, UAVs have started to be deployed to the FIFTH FLEET AOR onboard U.S. Navy DDGs for information, surveillance, and reconnaissance (ISR) support of current operations. First deployed onboard USS OSCAR AUSTIN (DDG 79) in November 2007, Boeing's Scan Eagle reached a milestone in April 2008 when it achieved its 1000th shipboard recovery (Aviation.com, 2008). While the future of such UAVs onboard MSO platforms remains undefined, the U.S. Navy has committed itself to their use and could be well served by a tool which would assist in the determination of an appropriate procurement strategy.

B. OBJECTIVES AND BENEFITS OF STUDY

We develop a decision support tool that incorporates software that can be implemented and shared by U.S. and coalition naval personnel for the scheduling of MSO ships in any given AOR. Additionally, the data it produces is useful for performing a study in the procurement and deployment of UAVs by the U.S. Navy.

The scope of this thesis is to develop a ship scheduling tool that will incorporate a given set of pre-existing mission commitments as parameters and provide an optimum employment strategy based on commander's intent and priorities. The tool utilizes common software such as Excel and Visual Basic so that it may be easily shared within

the DoD and among coalition partners. The output is a schedule that is feasible, easy to read, and compatible with existing reporting requirements.

II. DEVELOPMENTS IN SCHEDULING TOOLS, UAVS, AND LITERATURE REVIEW

A. MARITIME SCHEDULING TOOLS

Many scheduling tools have been developed for the purpose of optimally allocating assets for both military and non-military applications. Of particular note, tools that could be applied to the allocation of MSO assets are the Central-West Africa Resource and Mission Allocation model (CARMA) (Spitz, 2007) and the Navy Mission Planner (NMP) (Dugan, 2007). Both take into account the relative value of specific missions and/or locations from the commander's perspective, utilize integer programming, and deliver an optimal allocation for a given time horizon. But to the author's knowledge, there exists no maritime asset scheduling tool that incorporates the same relative value concept while incorporating logistical support constraints as input parameters. In a practical sense, ignoring these constraints or simply assuming that logistic support will be taken care of can produce a model that delivers an "optimal" solution which is ultimately infeasible (i.e., logistically unsupportable) in the real world.

While many other scheduling and logistics tools have been developed for a myriad of applications (Berner, 2007; Chng, 2007; DeGrange, 2004; Lape, 1993; & Lenhardt, 2001, to name a few), to the author's knowledge none exist that incorporate an adequately flexible rewards function, the ability to input pre-assigned port visits, in-chop and out-chop times, and (most importantly) underway replenishment schedules in a tool that would be compatible with existing U.S. and coalition computer operating systems and software.

1. Central-West Africa Resource and Mission Allocation Model

The Central-West Africa Resource and Mission Allocation model bridges the strategic and operational levels of planning to maximize presence or effectiveness of a set of maritime assets in a given AOR. This mixed-integer program is constrained by a budget, port costs, multiple penalty functions, and fuel. Relying on the Global Fleet

Stationing (GFS) concept, the CARMA model seeks to provide an optimal logistics-based strategy for deploying U.S. assets to engage in Theater Security and Cooperation (TSC) missions with the nations on the Gulf of Guinea (GOG). Designed to improve on solving the standard Vehicle Routing Problem, CARMA allows for multiple layers of reward functions to optimize prioritized (and sometimes conflicting) mission objectives (Spitz, 2007).

While CARMA has been implemented as a strategic-to-operational tool for planning resource allocation in the GOG, there remains the potential to expand this concept to tasking from a lower level commander on a shorter time horizon than that utilized in the model, providing an opportunity for ships to be further allocated so support multinational operations. In its current form, it provides for planning deployment schedules for the entire spectrum of U.S. assets to be deployed to the GOG, and is therefore inherently limited (for the sake of multi-national MSO asset allocation) by its connection to U.S. Navy budgeting and its being geared towards platforms designed for compatibility with GFS. Furthermore, it relies on GAMS/CPLEX (Spitz, 2007) for computing solutions—software that is unlikely to be at the disposal of afloat U.S. or coalition commanders.

2. Navy Mission Planner

The Navy Mission Planner optimizes multiple schedules for assets assigned to a specific AOR based on their possible movements, specific ship capabilities, and deconflicting incompatible missions. NMP allows for a theater commander to set reward values based on mission priorities for a given time horizon, and finding an optimal schedule for a set of ships over that time period. NMP, however, does not account for logistics requirements for the ships assigned to the given AOR. Additionally, it is designed to accommodate a set of possible warfare capabilities for a given array of U.S. ships, some of which may be classified. These limitations therefore do not lend NMP well for application toward multinational resource allocation for a more narrow and unclassified set of missions. Although robust and quite flexible in allowing the assignment of priorities for a commander, it also falls short in its inability to incorporate

logistics requirements. Based in Excel and Visual Basic, it could be deployed for immediate use within the fleet, but will still require some modification to ensure its solutions are truly feasible and do not conflict with the constraints imposed by the availability of logistics assets (Dugan, 2007).

3. Combat Logistics Force Planning Tool

For the specific requirements associated with scheduling Combat Logistics Force (CLF) assets, the CLF Planning Model developed by (Borden, 2001) provides an optimal solution to the total number of short-ton days a given combat fleet experiences levels below a given safety stock. Most recently, this model has provided a data foundation for optimally moving shuttle ships within a given network between customers, waypoints, and resupply ports utilizing a Floyd-Warshall shortest path algorithm (Morse, 2008).

Of particular interest in this version of the CLF Planning Model is the utilization of Floyd-Warshall in optimizing the movement of a given set of assets, an approach that could prove useful in the development of an MSO scheduling tool. Furthermore, the results from this tool may provide reasonable parameters for predetermined replenishments-at-sea (RAS) around which our scheduling tool may optimize asset allocation.

B. MARITIME UAV DEVELOPMENT AND EMPLOYMENT

In 1999, the U.S. Navy's Unmanned Aerial Vehicle Program Manager published the Performance Specification for the Vertical Takeoff and Landing Tactical Unmanned Aerial Vehicle (VTUAV). Mandated to be deployable on CG 47 and DDG 51 class ships, the VTUAV shall be capable of at least 12 hours of continuous, sustained operations in a 24 hour period. Furthermore, its shipboard footprint shall not exceed that of SH-60B helicopters and the system shall be compatible with existing shipboard configurations. Under these conditions, the VTUAV would be deployable immediately upon delivery to the Navy, acting as an over the horizon, high-resolution sensor capable of remaining on station two to four times longer than existing LAMPS assets without the limitations associated with manned aircraft. This capability could act as a force

multiplier for MSO missions, reducing the distances traveled by ships to positively identify vessels of interest and improving situational awareness for commanders (VTUAV Spec Development Team, 1999).

An existing alternative, the fixed-wing Scan Eagle, has already been proven in a maritime environment. Deployed in November 2007, onboard USS OSCAR AUSTIN (DDG 79) in support of MSO in the FIFTH FLEET AOR, Scan Eagle has an operational endurance in excess of 20 hours and a logistics footprint significantly smaller than that mandated for the VTUAV program. In June 2008, the U.S. Navy awarded Boeing a \$65 million contract for future support with the Scan Eagle UAV system, having proven itself as viable for ISR missions onboard 15 U.S. Navy ships to date (Commeagle, 2008).

C. MARITIME SECURITY OPERATIONS IN NETWORK-CENTRIC WARFARE

In Grivell and Fewell (2008), a Bayesian network utilization model was used to demonstrate the value of intelligence when MSO assets were employed using a prioritized queue. In this model, significant changes in the efficacy of assigned forces are evident based on changes in a given concept of operations (CONOPS). In cases where the CONOPS permit an aggressive posture--where a boarding may be pre-empted to allow teams to switch to a higher-priority target upon discovery--or in cases where friendly or neutral vessels are in the majority, the model reveals an advantage to utilizing a Network Centric Warfare (NCW) approach. Defined by the authors as, "the conduct of military operations using networked information systems to generate a flexible and agile military force...independent of individual elements, and in which the focus of the warfighter is broadened away from...unit or platform concerns to give primacy to the...task group or coalition," the NCW advantage, however, was tempered by a diminishing returns effect. For example, if a commander's database of known vessels of interest in a given was only half populated, it was found to be two-thirds as valuable as a complete database. What remained constant, while at varying degrees, was the value of improved (or more accurate) information.

With information as the central force multiplier in NCW, expanding the role of UAVs in the execution of MSO would appear to be a cost-effective means of increasing the value of assets to be assigned for these missions. Furthermore, the results of the study suggest that the increase of employing assets for the sake of expanding battlespace awareness will result in a diminishing returns effect. We will allow for similar diminishing “rewards” in our decision support tool.

D. LITERATURE REVIEW CONCLUSIONS

In light of the shortcomings and strengths of the many tools already in existence, it is the author’s belief that a scheduling tool for the effective allocation of coalition MSO assets should be based in Excel and Visual Basic. This tool should also allow for input parameters such as predetermined logistics requirements and port visits, and give commanders an optimal solution based on his or her stated priorities, intelligence, seasonal maritime traffic patterns, ship capabilities, target density, and region-specific functions that can provide for diminishing returns or a multiplicative effect with the introduction of additional assets.

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III. OPTIMAL SCHEDULING

A. SCHEDULING MODEL DEVELOPMENT

This chapter introduces a network optimization model for building a schedule based on reward criteria set by the CTF Commander. In this study, we are concerned with optimizing the daily locations and activities of a group of ships over a finite time horizon. Each ship on each day has a location (e.g. “Arabian Gulf”) and an activity, such as a port visit or RAS. We use a network model of the FIFTH FLEET AOR where each vertex represents a sea zone and an activity. Each edge in this network represents a transition from one of these pairs that can occur in one day. Certain locations, such as choke points, allow only one possible activity—transit between zones—to occur, and therefore have only one vertex associated with them. All four sea zones, however, allow for pre-scheduled port visits, RASs, in-chopping into, and out-chopping from the control of the CMF Commander (Figure 4).

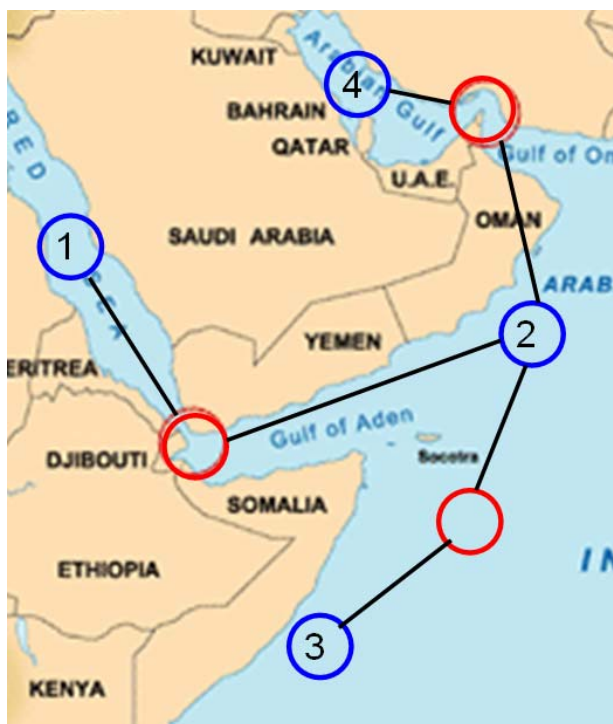


Figure 4. Geographic Network.

The time ships spend in the sea zone vertices conducting MSO is what we seek to maximize. In this geographic network illustrated in Figure 4, transit zones between sea zones are nodes that do not incur a reward, but may be scheduled to permit movement between sea zones to increase a ship's reward or to move toward a future obligation such as a port visit or a RAS. We have in this case four sea zones representing the Red Sea (vertex 1), the Arabian Sea (vertex 2), the Western Indian Ocean (vertex 3), and the Arabian Gulf (vertex 4) respectively. Adjacent to each sea zone in which MSO may be conducted, there are activity vertices. Figure 5 illustrates these adjacencies for sea zone 2, with vertices 50, 60, and 70 representing transit choke points, 12 representing a RAS, 22 a port visit, 32 in-chopping to the AOR, and 42 as out-chopping from the AOR.

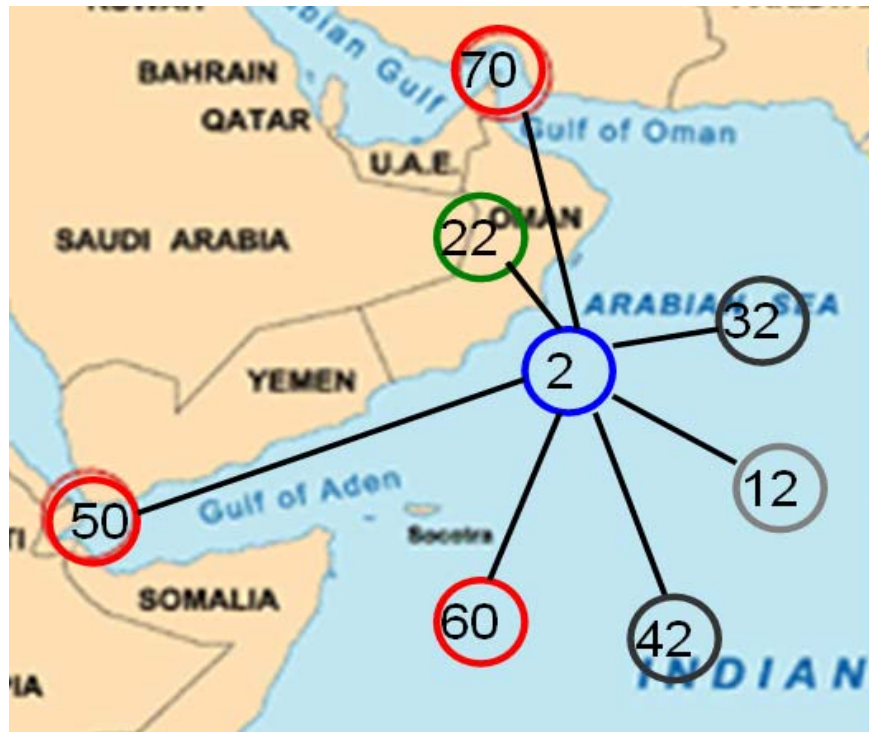


Figure 5. Adjacencies to Zone 2 in Geographic Network.

The desired outcome of the model we develop will be a schedule that maximizes the aggregate reward of all ships performing MSO missions on a notional timeline of fifteen days, while conforming to the physical and planning constraints represented in the geographic network.

1. Schedule Optimization Tools

A common hindrance to the deployment of scheduling tools developed in an academic environment is the software used to solve the optimization models. Most U.S. Navy activities do not possess software common to academia such as GAMS or MATLAB. Additionally, Navy and Marine Corps Intranet (NMCI) may not even support common commercial off-the-shelf (COTS) software packages that could run linear or nonlinear programming solvers. Almost universal, however, to Department of Defense and coalition partners is Microsoft Office, which includes Excel and Visual Basic (VBA) for applications.

2. Acyclic Network Longest-Path Approach

To achieve an optimal schedule, we construct an acyclic time-expanded *configuration network* as depicted in Figure 5. In this network, nodes represent feasible configurations of assets to be scheduled by the tool. A configuration is defined as a set of ships on a given day, each occupying any one of the twenty three location nodes in the geographic network. Given scheduling constraints and geographic adjacency limitations within the geographic network, not all configurations need to be considered for inclusion to the *configuration network*. Each node in the *configuration network* that is selected by a simple reaching algorithm adds its reward value to the total value of the longest path. A reward value is simply a number assigned to a given configuration based on its predetermined importance to a commander by way of the force presence it may provide in a theater. The resulting path would then represent the best possible feasible schedule that conforms to a commander's predetermined set of priorities based on intelligence, seasonal traffic patterns, historical successes and failures, task saturation, and any other quality declared important by the commander.

To build the *configuration network*, we take the first time step's configuration of ship locations as a given. As depicted in Figure 6, a column of configuration nodes is created in each following day based solely upon configurations which contain only ship positions that are geographically adjacent (and therefore feasibly reachable) in one time step for each ship. We define these feasible configurations as a state. Each resulting

state is then added to a state vector which consists of each possible configuration for the given time step. To produce arcs between nodes in each column vector, only feasibly reachable configurations are added to the forward star of each previous day's configuration node and given a cost that represents a predetermined reward value determined by the commander.

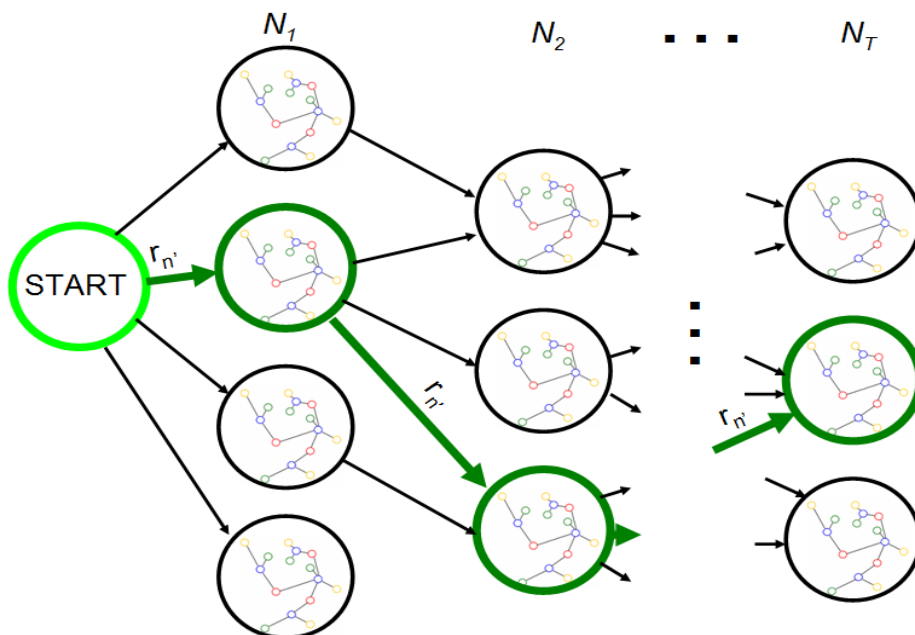


Figure 6. Time-Expanded Configuration Network.

We build the *configuration network* one day at a time and optimize the path as we build the network using dynamic programming, as explained in Ahuja, Magnanti, and Orlin (1993). The next section provides details about the formulation.

B. FORMULATION

This section formulates the ship scheduling problem as a longest-path problem in the *configuration network*. The Coalition Resource Allocation for Maritime Security (C-RAMS) scheduling tool utilizes a longest-path maximum-cost network flow linear program. C-RAMS seeks to maximize the reward value for the cumulative configurations (ship locations) in the geographic network for a given AOR.

Indices:

l	Locations in the geographic network. $l = 1, 2, 3, \dots, L$
s	Ships to be scheduled. $s = 1, 2, 3, \dots, S$
t	Time steps (e.g., day). $t = 1, 2, 3, \dots, T$
n	Configuration, where n represents a time period t and an S -dimension vector with the s^{th} component being the location of ship s in time period t .

$$n = \left\langle \begin{bmatrix} l_1 \\ l_2 \\ \vdots \\ l_S \end{bmatrix}, t \right\rangle$$

Sets:

N_t	Subset of all possible configurations in time period t determined by Network Building Algorithm, see below.
N	Set of possible configurations. $N = \cup_t N_t$ over all t
F_n	Forward star of configuration n determined by Network Building Algorithm, see below.
B_n	Reverse star of configuration n determined by Network Building Algorithm, see below.

Data:

r_n	Reward assigned for executing configuration n .
-------	---

Variables:

$X_{n,n'}$	1 if execution of configuration n' follows execution of n . 0 Otherwise.
------------	---

Formulation:

$$\max \sum_{n \in N, n' \in F_n} r_{n'} X_{n,n'}$$

s.t.

$$\sum_{n' \in B_n} X_{n',n} = \sum_{n' \in F_n} X_{n,n'} \quad \forall n \in N, n \notin N_T, n \notin N_1$$

$$\sum_{n \in N_1, n' \in F_n} X_{n,n'} = 1$$

$$X_{n,n'} \in \{0,1\} \quad \forall n, n'$$

Network Building Algorithm for Computing N_t , F_n , and B_n

Inputs: T vectors of pre-set ship obligations

$$C_t = \begin{bmatrix} l_{1,t} \\ l_{2,t} \\ \cdot \\ \cdot \\ \cdot \\ l_{S,t} \end{bmatrix}, t=1, 2, \dots, T, \text{ where}$$

$l_{s,t}$ is the predetermined location of ship s for time period t . If no commitment $l_{s,t} = 0$.

Outputs: Subset of all possible configurations within *configuration network* in

- time period t (N_t)
- Forward star of configuration n (F_n)
- Reverse star of configuration n (B_n)

Note: In this algorithm, by *feasibility* we mean a condition in which it is physically possible for a ship or a set of ships to move from one configuration to another.

Algorithm:

1. Create availability sets $A_{s,t}$ for each time period and ship as follows:
 - a. For every $s=1,2,\dots,S$, set
$$A_{s,1} = \{l_{s,1}\}$$
 - b. For $t = 2$ to T
 - For $s = 1$ to S
 - Construct $A_{s,t}$ as follows.
 - If $l_{s,t} > 0$, then set $A_{s,t} = \{l_{s,t}\}$.
 - Else, set $A_{s,t} = \{1, 2, \dots, L\}$
 - c. For $t = 2$ to T
 - For $s = 1$ to S

Reduce the size of $A_{s,t}$ by preprocessing. This is done by recursively scanning forward and backward from each $A_{s,t}$ and eliminating all configurations with one or more infeasible ship movements.

2. Then enumerate
 $N_1 = A_1$
for each $t=2 \dots T$
use $A_{s,t}, s=1, \dots, S$, enumerate possible configurations to create N_t .
3. Create forward and backward star from N_t .
 - a. For each configuration in t , check feasibility of executing configuration change to each configuration in $t+1$. If feasible, add to F_n .
 - b. For each configuration in t , check feasibility of executing configuration change to each configuration in $t-1$. If feasible, add to B_n .

C. REWARDS DETERMINATION AND ASSIGNMENT

To produce the reward data necessary for building the acyclic network, we define a function f , where f is specified by the user of the scheduling tool based on intelligence, commander's intent, specific ship capabilities, seasonal norms, etc. We define the reward of configuration n as

$$r_n = f\left(\begin{bmatrix} l_1 \\ l_2 \\ \vdots \\ l_s \end{bmatrix}, t\right)$$

In this thesis, we set f as the summation of predetermined reward values per ship s in location l in time period t multiplied by a function that allows a commander to model diminishing returns for adding ships to a given region as well as providing an additional bonus for not leaving any zones uncovered. In this case, we define $r_{l,s,t}$ as the reward for having ship s in location l in time period t .

1. Reward Update Module

To provide a sufficiently flexible input module for assigning rewards, a Reward Update Module (RUM) was built within C-RAMS. Each category of ships assignable is given a baseline reward value relative to other ship types on a given day. Then, each ship's relative value for being assigned in each zone is selected. The resulting value will provide that day's reward value for a given ship in a given zone. A base case can be selected from which each day in the given time horizon may be more quickly adjusted. For the sake of this study, ship type A is a U.S. Navy Cruiser or flight IIA DDG, type B is a U.S. Navy Flight I DDG, Type C is a U.S. Navy FFG or coalition warship without helicopters, Type D is a U.S. Navy FFG or coalition warship with helicopters, Type E is a U.S. Coast Guard Cutter or U.S. Navy PC, and Type F is reserved for another ship class. In this case we will call Type F U.S. Navy DDG Flight I with UAVs in order to study the effect on scheduling employing UAVs to these ships may have. This base case appears as seen in Figure 7, in which the column of slide bars on the left adjusts the baseline value of each ship type relative to each other and the array of slide bars on the right adjust the relative value of each ship type within each zone. The values highlighted in green represent the product of the zone and ship values to be called by the reward calculation subroutine.

Type	Base Scale		Zone 1	Zone 2	Zone 3	Zone 4
A	80	Relative Value	0.2	0.23	0.1	0.4
		Adjusted Value	18	18.5	12	32
B	60	Relative Value	0.2	0.2	0.3	0.3
		Adjusted Value	12	12	18	18
C	65	Relative Value	0.3	0.25	0.3	0.3
		Adjusted Value	16	16.3	16	16
D	72	Relative Value	0.3	0.25	0.3	0.3
		Adjusted Value	18	18	18	18
E	40	Relative Value	0.2	0.28	0.1	0.4
		Adjusted Value	8.8	11.2	4	16
F	75	Relative Value	0.2	0.2	0.3	0.3
		Adjusted Value	15	15.1	22	23

Figure 7. Ship Type and Zone Reward Assignment in RUM.

Next, the diminishing (or increasing) returns values are set for each zone. To set these values, we define a Marginal Rewards Multiplier (MRM) λ as

$$\lambda_x = \frac{e^{(1.5)}}{e^{(x^\rho + \frac{1}{2x})}}$$

where x is a sequence number assigned to a each ship within a given zone. For example, λ_1 is the MRM for the first ship, λ_2 is the MRM for the second ship, and so on. The variable ρ is a decay rate which is an adjustable value that allows the returns to increase or diminish for each additional ship added to a zone at a rate determined by the commander. In our case, each λ_x is multiplied by the raw reward value for a given ship s in location l in the order in which ships were assigned to be scheduled. This allows for commanders to prioritize which ships may incur the greatest penalty within the diminishing returns function. The changes in the cumulative effects of adding more ships to a given zone can be represented by adjusting ρ as depicted in Figure 8. In this case, the y-axis represents the number of ships worth of effectiveness that exist in a given region and the x-axis represents the actual number of ships assigned to that region.

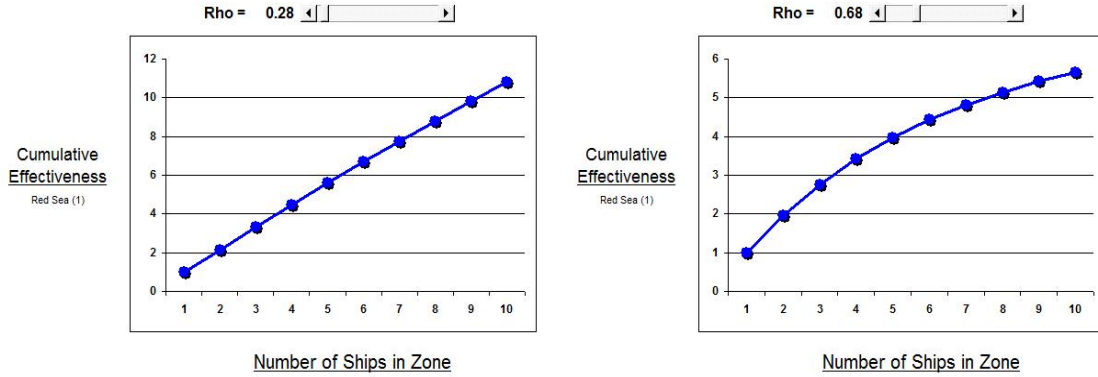


Figure 8. Cumulative Effects of $\rho = 0.28$ and $\rho = 0.68$.

Finally, an all-zones coverage coefficient, ϕ , is multiplied to the resultant reward from each configuration.

2. UAV-Based Rewards Augmentation

To provide the ability to study the effects of augmenting a given platform with UAVs, an additional ship type is added to the RUM to allow for its theoretical rewards to be set. The same open ship type may be also used to measure the effects of other advancements that improve the effectiveness of a given platform in performing MIO.

D. SCHEDULE EXTRACTION

To attain the end result and promulgate a schedule for ships assigned to the CMF commander, a macro is produced to extract the individual daily configurations from a log file produced by C-RAMS. These configurations are then translated into fifteen vectors of ship names and geographic locations. Finally, the daily and cumulative reward values are displayed in a table in order to provide data which may be used to perform sensitivity analyses and measure the effects of changing input parameters.

IV. ANALYSIS

A. CASE STUDY

In order to establish a baseline set of data from which analyses can be made, relative zone reward, relative ship reward, all zone coverage multiplier, and diminishing returns multipliers are chosen. All rewards are selected to be uniform throughout the notional scheduling period and set to the values shown in Table 1. In this base case, not all ships are assumed equally effective in performing MSO in every sea zone. For example, the small size and relatively smaller radar and communications capabilities of a U.S. Navy PC make it less desirable to patrol in the Arabian Sea/Western Indian Ocean than in the Arabian Gulf. Furthermore, it is assumed that a US Navy cruiser, with its robust radar and communications capabilities as well as embarked LAMPS assets would be more effective in general than a U.S. Navy frigate with no helicopters. To begin with, there is no value given to ship type F, a U.S. Navy Flight I DDG with UAVs. The bold italicized numbers in Table 1 represent the values returned to the rewards subroutine (for example a Flight I DDG in zone 3 would return 17.6).

		Zone				
		Base Value	1	2	3	4
A	CG/IIADDG	80	17.7	18.5	11.8	32
B	FI DDG	60	12	12	17.6	18.4
C	US FFG/COALITION FFG NO HELO	65	16.3	16.3	16.3	16.3
D	US FFG/COALITION FFG WITH HELO	72	18	18	18	18
E	USCGC/PC	40	8.8	11.2	4	16
F	FI DDG W/ UAV	75	15.1	15.1	21.6	23.1

Table 1. Sample Default Reward Values from C-RAMS

Next, the diminishing returns value, ρ , is selected for each zone, resulting in four distinct decay curves which represent a cumulative value as ships are added to a given sea zone. For example, in this case five ships assigned to the Red Sea incur a penalty which makes them essentially as effective as four ships (as seen in Figure 9).

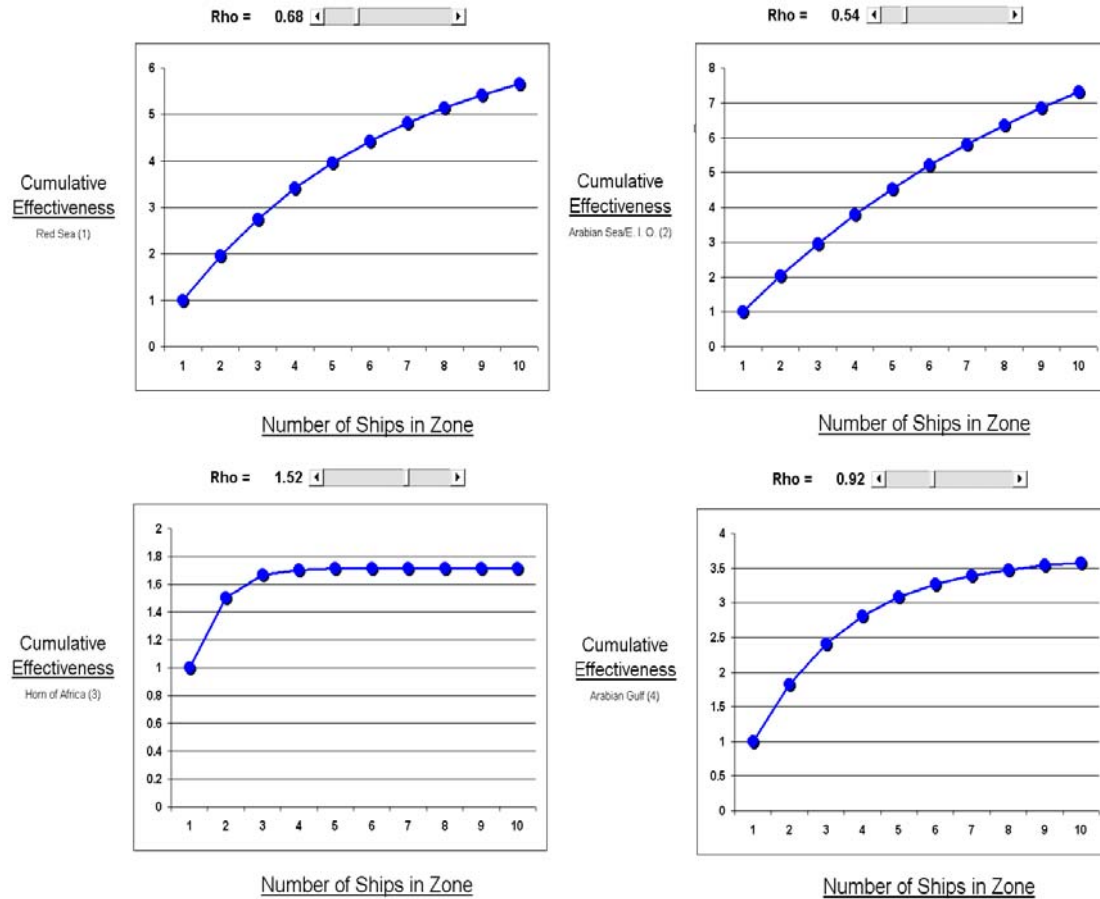


Figure 9. Sample Diminishing Returns Multiplier Graphs from C-RAMS.

After building a baseline for rewards, a set of scenarios are selected, each of which may have one to three parameters altered to determine the scheduling tool's flexibility and sensitivity to changes. Since one of the major aims of this study is to effectively analyze the future utility of employing UAVs on MSO missions, four U.S. Navy Flight I DDGs are selected as the focus of our analysis. In order to account for all four operational zones and to initially eliminate the possibility of interaction effects with other ship types, these ships were set up in the model, each with a single different

commitment (such a port visit or RAS) scheduled as parameters on the fifteen day time horizon and each beginning this scheduling period in the Arabian Sea (zone 2). The inputs for this scenario can be seen in Figure 10, with the green “0” days open for assignment by the C-RAMS program.

Ship Symbol	LAB	OKE	GON	STO
Type	US F1DDG	US F1DDG	US F1DDG	US F1DDG
Code	B	B	B	B
Julian				
1	GOA/NWIO	GOA/NWIO	GOA/NWIO	GOA/NWIO
	2	2	2	2
2	Open For Ass	Open For Ass	Open For Ass	Open For Ass
	0	0	0	0
3	Open For Ass	Open For Ass	Open For Ass	Open For Ass
	0	0	0	0
4	RAS-RS	Open For Ass	Open For Ass	Open For Ass
	11	0	0	0
5	Open For Ass	Open For Ass	Open For Ass	Open For Ass
	0	0	0	0
6	Open For Ass	Open For Ass	Open For Ass	Open For Ass
	0	0	0	0
7	Open For Ass	RAS-GOA/AS	Open For Ass	Open For Ass
	0	12	0	0
8	Open For Ass	Open For Ass	Open For Ass	Open For Ass
	0	0	0	0
9	Open For Ass	Open For Ass	Open For Ass	Open For Ass
	0	0	0	0
10	Open For Ass	Open For Ass	Open For Ass	Open For Ass
	0	0	0	0
11	Open For Ass	Open For Ass	Open For Ass	Open For Ass
	0	0	0	0
12	Open For Ass	Open For Ass	RAS-HOA	Open For Ass
	0	0	13	0
13	Open For Ass	Open For Ass	Open For Ass	Open For Ass
	0	0	0	0
14	Open For Ass	Open For Ass	Open For Ass	Open For Ass
	0	0	0	0
15	Open For Ass	Open For Ass	Open For Ass	Port-AG
	0	0	0	24

Figure 10. Initial Inputs for Baseline Scenario in C-RAMS.

Next, sixteen scenarios are built in C-RAMS with modifications to various parameters made as illustrated in Table 2.

<u>Scenario</u>	<u>Number of Ships</u>	<u>All zones coverage coefficient</u>	<u>Number of UAVs</u>	<u>Relative UAV value to Helicopter</u>	<u>Notes</u>
1	4	1	0	N/A	
2	4	1.15	0	N/A	
3	4	1	0	N/A	<i>One predetermined commitment changed from scenarios 1 and 2</i>
4	4	1.25	0	N/A	<i>One predetermined commitment changed from scenarios 1 and 2</i>
5	4	1	0	N/A	
6	4	1.25	0	N/A	
7	10	1.15	0	N/A	
8	10	1.25	0	N/A	
9	10	1.25	1	0.75	
10	10	1.25	2	0.75	
11	10	1.25	3	0.75	
12	10	1.25	4	0.75	
13	10	1.25	1	1.25	
14	10	1.25	2	1.25	
15	10	1.25	3	1.25	
16	10	1.25	4	1.25	

Table 2. Scenario Characteristics

B. SCHEDULING FOUR U.S. NAVY FLIGHT I DDGs

The first six scenarios modeled consist exclusively of the four U.S. Navy Flight I DDGs. We chose USS LABOON, USS OKANE, USS GONZALEZ, and USS STOUT as our sample assets. After the first scenario is run, the expected outcome was realized, with each ship dispersing to all four zones in which they had a pre-programmed commitment and then migrated to zones with the two highest relative reward values for their ship type.

After scenario 1, there first change was to study the effect of a bonus for having covered all four zones. With all else the same as the first scenario, scenario 2 had the four ships starting out as before, but remaining in each of the four zones, selecting the configuration that would give them a 15% increase in aggregate reward value for an additional seven days.

The third scenario (Table 3) was set to be the same as the first, but instead of having a different commitment in one of each of the zones, the second ship was pre-scheduled for a port visit on the seventh day in the Horn of Africa zone. Since this zone (along with the Arabian gulf) are the two highest reward zones in this scenario, the ships again ended up occupying these zones following the first ship's scheduled RAS in the Red Sea on day 4.

In our fourth scenario (Table 3), the same initial parameters from the third scenario were left in place, however an all zones coverage bonus of 25% was set. After running the program, each ship behaved as they did in the beginning of the first scenario, but dispersed to all for zones when possible after completing each preset assignment as before as the all zones coverage bonus dominated the value of two of the ships occupying zones 3 and 4 as in the third scenario.

Scenarios 5 and 6 set began just as the first, but in each of these cases the relative reward for occupying zone 2 was made to dominate all others for days seven through nine (Table 3). As would be expected, in the scenario in which no multiplier incentivized movement to all four zones, all four ships loitered or returned to zone two until after day 9. For the final five days, the ships would be returned to the same destinations as before, with two each in zones 3 and 4, or dispersed to all four zones with an all zones bonus of 25%.

In order to see the effects of changing these various parameters, Table 3 depicts the daily locations of LABOON (LAB), OKANE (OKE), GONZALES (GON), and STOUT (STT) when in a sea zone accruing rewards for these first six scenarios, the characteristics of which are depicted in Figure 10.

Scenario 1														
1			LAB		LAB									
Zone 2	LAB, OKE GON, STT	OKE	OKE	OKE	OKE	OKE	LAB	OKE						
3			GON	GON	GON	GON	GON	GON	GON	OKE, GON	OKE, GON	OKE, GON	OKE, GON	OKE, GON
4				STT	STT	STT	STT	STT	LAB, STT	LAB, STT	LAB, STT	LAB, STT	LAB, STT	LAB, STT
DAY														
Scenario 2														
1			LAB		LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB
Zone 2	LAB, OKE GON, STT	OKE	OKE	OKE	OKE	OKE		OKE	OKE	OKE	OKE	OKE	OKE	OKE
3			GON	GON	GON	GON	GON	GON	GON	GON	GON		GON	GON
4			STT	STT	STT	STT	STT	STT	STT	STT	STT	STT	STT	STT
DAY														
Scenario 3														
1			LAB		LAB									
Zone 2	LAB, OKE GON, STT						LAB							
3			OKE, GON	OKE, GON	OKE, GON	OKE, GON	OKE, GON	OKE, GON	OKE, GON	OKE, GON	OKE, GON	OKE, GON	OKE, GON	OKE, GON
4				STT	STT	STT	STT	STT	LAB, STT	LAB, STT	LAB, STT	LAB, STT	LAB, STT	LAB, STT
DAY														
Scenario 4														
1			LAB		LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB
Zone 2	LAB, OKE GON, STT	GON	GON	GON	GON	GON	GON	GON	GON		OKE	OKE	OKE	OKE
3			OKE	OKE	OKE	OKE		OKE	OKE		GON		GON	
4				STT	STT	STT	STT	STT	STT	STT	STT	STT	STT	STT
DAY														
Scenario 5														
1			LAB		LAB									
Zone 2	LAB, OKE GON, STT	OKE GON, STT	OKE GON, STT	OKE GON, STT	OKE GON, STT	OKE GON, STT	LAB GON, STT	LAB, OKE GON, STT						
3										LAB, GON	LAB, GON	LAB	LAB, GON	LAB, GON
4										OKE, STT	OKE, STT	OKE, STT	OKE, STT	OKE, STT
DAY														
Scenario 6														
1			LAB		LAB					LAB	LAB	LAB	LAB	LAB
Zone 2	LAB, OKE GON, STT	OKE	OKE	OKE	OKE	OKE GON, STT	LAB GON, STT	LAB, OKE GON, STT	OKE	OKE	OKE	OKE	OKE	OKE
3			GON	GON						GON	GON		GON	GON
4			STT	STT						STT	STT	STT	STT	STT
DAY														

Table 3. Optimal Ship Allocation for Scenarios 1 - 6 in C-RAMS

C. SCHEDULING TEN SHIPS

In order to demonstrate the interactive effects of up to ten ships in C-RAMS, the remaining six ship columns were populated in the input interface. In order to measure the effects on differences to the schedules of the original four DDGs, the same input parameters for these remaining six vessels were constant through all scenarios. For this set of scenarios, these new input parameters were added to scenarios 2 and 6 (Table 2), two from the original group for which an all zones coverage bonus was available. The set of input parameters for the seventh scenario illustrates this as seen in Figure 11.

Ship Symbol	LAB	OKE	GON	STO	JPG	NOR	TYP	LIB	DUA	CHV
Type	US F1 DDG	US F1 DDG	US F1 DDG	US F1 DDG	Coalition w/H	US CG/F2A D	Coalition w/O	US CG/F2A D	Coalition w/H	Coalition w/H
Code	B	B	B	B	D	A	C	A	D	D

Julian	GOA/NWIO	GOA/NWIO	GOA/NWIO	GOA/NWIO	HQA/WIO	Arabian Gulf	Port-AG	InChop-AG	HQA/WIO	InChop-RS
1	2	2	2	2	3	4	24	34	3	31
2	Open For Ass	Open For Ass	Open For Ass	Open For Ass	HQA/WIO	Open For Ass	Port-AG	InChop-AG	Open For Ass	InChop-RS
3	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Port-AG	Open For Ass	InChop-AG	Open For Ass	InChop-RS
4	RAS-RS	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Port-AG	Open For Ass	InChop-AG	Open For Ass	InChop-RS
5	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Port-AG	Open For Ass	InChop-AG	Open For Ass	Open For Ass
6	Open For Ass	Open For Ass	Open For Ass	Open For Ass	RAS-GOA/IAS	Open For Ass	Open For Ass	InChop-AG	Open For Ass	Open For Ass
7	Open For Ass	RAS-GOA/IAS	Open For Ass	Open For Ass	Open For Ass	Open For Ass	RAS-AG	InChop-AG	RAS-AG	Open For Ass
8	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Open For Ass	InChop-AG	Open For Ass	Open For Ass
9	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Open For Ass	RAS-AG	Open For Ass	InChop-AG	Open For Ass	RAS-GOA/IAS
10	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Open For Ass	OutChop-AG	Open For Ass
11	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Port-RS	Open For Ass	Open For Ass	Open For Ass	OutChop-AG	Open For Ass
12	Open For Ass	Open For Ass	RAS-HQA	Open For Ass	Port-RS	Open For Ass	OutChop-GQ/	Open For Ass	OutChop-AG	Open For Ass
13	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Port-RS	Open For Ass	OutChop-GQ/	Open For Ass	OutChop-AG	Open For Ass
14	Open For Ass	Open For Ass	Open For Ass	Open For Ass	Port-RS	Open For Ass	OutChop-GQ/	Open For Ass	OutChop-AG	Port-AG
15	Open For Ass	Open For Ass	Open For Ass	RAS-AG	Open For Ass	RAS-AG	OutChop-GQ/	RAS-AG	OutChop-AG	Port-AG

Figure 11. Initial Inputs for Baseline Scenario in C-RAMS.

In the seventh scenario there is no change from that seen in the second. Since there were no increased rewards by day, nor significant penalties assigned through the diminishing returns function, the program had no incentive to schedule unnecessary movements through transit zones which incur no reward (Table 4).

In the eighth scenario (based on scenario 6 in which zone 2 was given a higher reward value), some of the other assets remained in enough of the other zones to ensure the daily 25% all zones coverage bonus was earned while otherwise scheduling as many ships as possible in zone 2 on the most valuable days. The resulting schedules for these four ships in these two scenarios are illustrated in Table 4.

Scenario 7															
Zone	1		LAB		LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB
	2	LAB, OKE GON, STT	OKE	OKE	OKE	OKE	OKE		OKE	OKE	OKE	OKE	OKE	OKE	OKE
	3		GON	GON	GON	GON	GON	GON	GON	GON	GON		GON	GON	GON
	4		STT	STT	STT	STT	STT	STT	STT	STT	STT	STT	STT	STT	
DAY															

Scenario 8															
Zone	1		LAB		LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB
	2	LAB, OKE GON, STT	OKE, STT	OKE, STT	OKE, STT	OKE, STT	OKE, STT	STT	OKE, STT	OKE	OKE	OKE	OKE	OKE	OKE
	3		GON	GON	GON	GON	GON	GON	GON	GON	GON		GON	GON	GON
	4									STT	STT	STT	STT	STT	
DAY															

Table 4. Optimal Ship Allocation for Scenarios 7 and 8 in C-RAMS

D. SCHEDULING FLIGHT I DDGs WITH UAVs

To explore the sensitivity of the scheduling results to augmenting U.S. Navy Flight I DDGs with UAVs, eight scenarios were built and run building off of scenario 8 (Table 2).

If we assume that employing a UAV on a DDG is 75% as effective as employing a LAMPS helicopter for performing MSO missions, we may set a relative reward value to ship type F that encapsulates this change to the capabilities now available to the CMF Commander. We then modify scenario 8 to reflect this change and run the model four times, one for each additional augmentation.

Next, if we assume employing a UAV increases a ship's mission effectiveness, we can set an upper bound in our scenarios with the value of UAVs at 125% of that provided under normal circumstances by LAMPS platforms. Again, four scenarios are run, each adding one UAV capable DDG more than the previous.

After running these eight scenarios, a gradual change in scheduling outputs was discovered. For the first five of these scenarios, the actual schedule did not change, however a gradual increase in reward values for the scheduling period were realized. In scenario 14, however, when two UAV augmented ships are scheduled, ship 2 (a non-UAV asset) would migrate between zones 1 and 2, the two zones with the lowest rate of diminishing returns per ship added. Finally, for the last two scenarios the ships were set to execute the same schedule as resulted from scenarios 9, 10, 11, 12, and 13, with the least coverage being scheduled in zones with higher rates of decay in the diminishing rewards function, leaving assets from the pool of the other six ships to cover those areas. Table 5 illustrates the daily position of these ships through the eight UAV augmented scenarios.

Scenarios 9, 10, 11, 12, and 13

Zone	1			LAB		LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	
	2	LAB,OKE GON,STT	OKE,STT	OKE,STT	OKE,STT	OKE,STT	STT	OKE,GON	OKE	OKE	OKE	OKE	OKE	OKE	OKE	
	3			GON	GON	GON	GON	GON	GON	GON	GON		GON	GON	GON	
	4									STT	STT	STT	STT	STT		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		DAY														

Scenario 14

Zone	1			LAB,OKE	OKE	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	
	2	LAB,OKE GON,STT	STT	STT	STT	STT	OKE,STT	STT	OKE,STT	OKE	OKE	OKE	OKE	OKE	OKE	
	3			GON	GON	GON	GON	GON	GON	GON	GON		GON	GON	GON	
	4									STT	STT	STT	STT	STT		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		DAY														

Scenarios 15 and 16

Zone	1			LAB		LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	LAB	
	2	LAB,OKE GON,STT	OKE,STT	OKE,STT	OKE,STT	STT	OKE,STT	OKE,STT	OKE,STT	OKE	OKE	OKE	OKE	OKE	OKE	
	3			GON	GON	GON	GON	GON	GON	GON	GON		GON	GON	GON	
	4										STT	STT	STT	STT	STT	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		DAY														

Table 5. Ship Allocation for Scenarios 9 through 16 from C-RAMS

To demonstrate the improved relative expected effectiveness in performing MIO by augmenting Flight I DDGs with UAVs, the resulting reward values from all eight of these scenarios were plotted to illustrate the percentage increase in UAV employment reward effects. As illustrated in Figure 12, if our assumptions hold true and UAVs worth 75% of a helicopter detachment are assigned to Flight I DDGs, the entire task force's

effectiveness is increased by 3%. Conversely, a 6% increase in effectiveness is realized throughout the scheduling period if the assumption that a UAV's value is 125% that of a helicopter detachment for performing MSO.

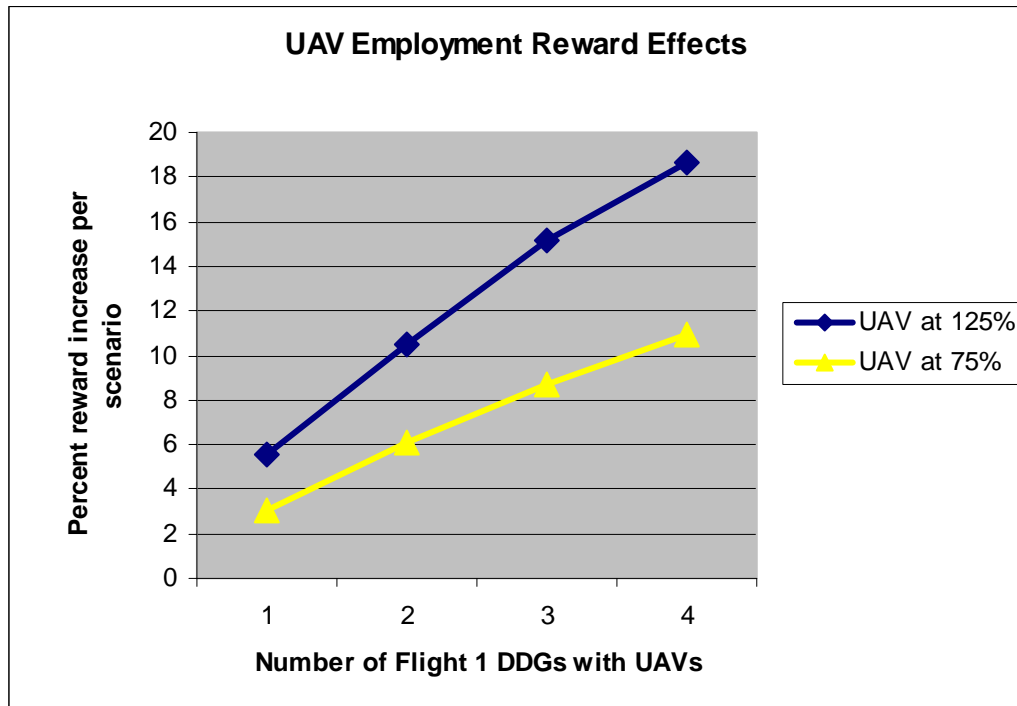


Figure 12. UAV Employment Reward Effects.

E. RUN TIME AND PROBLEM SIZE

For the first six scenarios in which the program had only four ships to schedule, the program generated between 3500 and 4000 states and took 16 seconds to find an optimal solution. Conversely, when the larger scenarios were run with ten ships, more than 37,000 states were generated and the program took just under six minutes to return its optimal result. All scenarios were run on a Pentium 4 with 3.2 GHz of processor speed and 2 MB of memory. It was observed that more predetermined ship commitments resulted in faster run times as well as shorter time periods between preset commitments.

At no point was it observed that run time was affected by changing any parameters in the RUM. Furthermore, since the dynamic program only creates feasible state spaces, attempts to assist the program by populating the input interface with obvious adjacent locations (zone 2 following a RAS in zone 2 for example) did nothing to reduce the size of the problem or run time.

While C-RAMS is sufficient for ten ships on a fifteen day scheduling horizon, the addition of ships and planning days would increase the size of the problem at an exponential rate and likely exceed the capabilities of the current architecture's implementation on comparable computer systems. For larger problems, either a machine with more computational power or a heuristic to more efficiently build state spaces and solve *configuration network* would be helpful.

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V. CONCLUSIONS AND RECOMMENDATIONS

We have developed the Coalition Resource Allocation for Maritime Security (C-RAMS) decision support tool that may easily be implemented and shared by US and coalition naval personnel for the scheduling of Maritime Security Operations (MSO) ships in the FIFTH FLEET Area of Responsibility. This scheduling tool incorporates a given set of pre-existing mission commitments as parameters and provides an optimum employment strategy based on commander's intent and priorities. Programmed in Excel and Visual Basic, it may be easily shared within the DoD or among coalition allies. The output is a schedule that is feasible, and compatible with existing reporting requirements.

For each of the sixteen scenarios we examined, the optimal solutions resulted in an average of four out of 240 ship-days being scheduled to be in a sea zone in which no reward is accrued. While no baseline data exists from which an improvement may be measured, the optimal schedules produced by C-RAMS provide an insight to how many ship-days may currently be inefficiently allocated.

Given the flexibility of the rewards update module, C-RAMS allows for further study in the efficacy of UAVs as an organic asset to US Navy ships conducting MSO. Furthermore, C-RAMS may be used to make recommendations for the procurement and deployment of UAVs based on the added capabilities of a given system to US assets assigned to the Combined Maritime Force. Given the demonstrable effects in our of scenarios of increasing overall presence rewards by 3 to 19 percent with the addition of UAVs, it is recommended that a larger set of scenarios is run within a larger study of maritime UAV employment strategies. Furthermore, the results from the scenarios examined in this thesis included the entire set of ships available to the CMF Commander, thereby including interaction effects between ships. For non-coalition based scheduling or UAV research, it is recommended that scenarios are run that include only U.S. Navy platforms for which UAV employment is being considered.

The rewards used in the scenarios considered in this study were based on perspectives shared by U.S. Navy Surface Warfare Officers and the author's experience. Future studies which utilize C-RAMS should include a robust analysis of ship capabilities and the effects of interactions between ships in a given region. While the Reward Update Module is flexible enough to allow a wide range of reward values, it is designed to provide reasonable data for studying the scheduling tool, not a proven real-world database upon which operational decisions can be made.

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